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Argonne National Laboratory

PHYSICS DIVISION SUMMARY REPORT

October—December 1970

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Physics

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

PHYSICS DIVISION SUMMARY REPORT

October—December 1970

Lowell M. Bollinger, Division Director

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FOREWORD

The Physics Summary is issued several times per year for the information of the members of the Division and a limited number of other persons interested in the progress of the work. It includes short reports on highlights of the current research, abstracts or short summaries of oral presentations at meetings, abstracts of papers recently accepted for publication, and publication notices of papers appearing in recent journals and books. Many of these reports cover work still in progress; the results and data they present are therefore preliminary, tentative, and often incomplete.

The research presented in any one issue of the Summary is only a small random sample of the work of the Physics Division. For a comprehensive overview, the reader is referred to the ANL Physics Division Annual Review issued each summer, the most recent being Argonne National Laboratory Report ANL-7728, which reports research in the year ending 31 March 1970.

The issuance of these reports is not intended to constitute publication in any sense of the word. Final results will be submitted for publication in regular professional journals or, in special cases, presented in ANL Topical Reports.

FOREWORD

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TABLE OF CONTENTS

I. RESEARCH HIGHLIGHTS

These research highlights are Physics Division contributions to the Physical Research Monthly Report which the Laboratory Director's Office sends to the Division of Research of the U. S. Atomic Energy Commission. They report interesting work that is currently in progress or that has just been completed.

THE LOW-ENERGY PHYSICS RESEARCH PROGRAM AT CP-5

After 15 years of operation, the research reactor CP-5 was shut down in January 1969 in order that the facility could be thoroughly rehabilitated. During the following 22 months, the control and primary-cooling systems were rebuilt, the ventilation and electrical-distribution systems were modified, the containment shell was improved, the beam-gate drives were replaced, the rabbit facilities were rebuilt, and the operating characteristics connected with the safety of the reactor were thoroughly studied. The reactor was brought back to regular full-power operation in late October 1970. The long down time of the reactor did not result in any important improvements in reactor characteristics, from the point of view of the user, but presumably the rebuilding will lead to many more years of useful operation.

In the past, research supported by the Low-Energy Physics program has been one of the major activities at CP-5, and this productive program will continue. The renewed research falls into two general areas: (a) fundamental experiments with thermal neutrons and (b) studies of neutron-capture γ rays. A third area that was formerly important, the measurement of neutron cross sections with a fast neutron chopper, has been discontinued for lack of the manpower required to justify the costs involved in maintaining the equipment.

Fundamental Experiments

Just before the reactor was shut down, three fundamental experiments were carried out at CP-5: (1) a study of the weak interaction by measuring the asymmetries in the decay of polarized neutrons, (2) a search for parity nonconservation in the strong interaction by observing the parity-forbidden α decay of a state in ^{16}O, and (3) a measurement of Delbrück scattering. In view of the interest and importance of these experiments, they all are being repeated with improved equipment and techniques developed during the reactor shutdown. These are described individually in the next three paragraphs.

Delbrück scattering (H. E. Jackson and K. J. Wetzel). This process is the elastic scattering of photons by the Coulomb field of the nucleus. The effect was first observed clearly in an experiment carried out at CP-5 in 1968. The experiment has been improved greatly by the installation of a new collimation system and a better detector. A refined new set of measurements was completed during the first two months after the reactor resumed operation (November and December 1970), and these new data are being analyzed. In addition to providing information about the elastic scattering of 10.8-MeV photons by ^{238}U, the new data will give an accurate measurement of the cross section for inelastic scattering (nuclear Raman scattering) to the first excited state, an entirely new kind of information.

Parity nonconservation (R. E. Segel, E. L. Segel, W. Corwin, and L. Greenwood). The experiment at CP-5 involves an effort to measure the degree of parity nonconservation in the strong interaction by detecting the extremely weak parity-forbidden α decay of the 2^- state at 8.8 MeV in ^{16}O. This state is formed by the β decay of the ^{16}N nuclei that are generated in the reactor core by the reaction $^{19}F(n,\alpha)^{16}N$. During the past year, the experiment has been improved greatly by the solution of the technical problems involved in the collection of the active ^{16}N atoms of interest. The new measurements, which will start in February 1971, are expected to yield data of very much better accuracy than have been obtained heretofore.

Decay of polarized neutrons (V. E. Krohn and G. R. Ringo). Various parameters of the weak interaction can be obtained from the asymmetries in the decay of polarized neutrons. For a number of reasons—the best of which may be the puzzling decay of the K_L^0 particle—the weak interaction is as interesting as anything in physics today. The decay of the free neutron gives the best available chance to measure accurately the fundamental parameters of the non-strange weak interaction. Three of the parameters are obtainable from correlation measurements on the decay of polarized neutrons, and hence there is great interest in improving the accuracy of such measurements. The experiment completed at CP-5 in 1968 had many refined features but, because it was cut off by the shutdown of the reactor, it did not have the hoped-for statistical accuracy. Thus, a new series of measurements will soon be started with an improved polarizer.

Neutron-Capture γ Rays

Research on neutron-capture γ rays is carried out at CP-5 with four major experimental systems—probably the world's most refined and varied experimental setup for neutron-capture γ-ray spectroscopy. The status of each of these systems is outlined below.

Internal-target facility (L. M. Bollinger, G. E. Thomas, and R. K. Smither). This system is used for the measurement of high-energy (n, γ) transitions in general, and in particular for the measurement of average-resonance-capture spectra—i.e., the spectra from the capture of neutrons in a group of resonances. During the shutdown of the reactor, a large body of data obtained with this system was analyzed. The results have shown the power of the average-resonance-capture method for determining the spins and parities of low-energy nuclear states. Measurements of this kind have been resumed.

Bent-crystal spectrometer (R. K. Smither and D. L. Bushnell). During the shutdown, substantial improvements in the system were carried out. These include improvements in the source-handling system, the aim being to provide better geometrical stability of the source. Also, the electronic control system was modified. During December, exploratory measurements were made on a new diffraction crystal; and new studies of nuclear energy levels will commence in February.

Ge(Li)-Ge(Li) coincidence system (H. H. Bolotin). During the shutdown this highly developed coincidence system (the first of its kind) was improved by the expansion of the data-storage matrix and by conversion to computer-compatible tape.

Internal-conversion spectrometer (S. B. Burson). This instrument is a new kind of spectrometer in which internal-conversion electrons are funneled onto a solid-state detector by means of a superconducting solenoid magnet. Because of its large acceptance angle and the fact that all energies are recorded simultaneously, this system has a much higher detection efficiency than the competing magnetic spectrographs. Also, the capability of carrying out β-γ coincidences is an important advantage. Preliminary tests carried out before the reactor was shut down showed that the spectrometer itself works well, but the background counting rate was higher than was desired. To correct this difficulty, the thermal column at which the spectrometer was located was completely rebuilt during the shutdown. If this effort was successful, as expected, we will have an intense beam of thermal neutrons that is exceptionally free of unwanted fast neutrons and gamma radiation. The improved system will be used intensively during the next six months.

The abstracts and summaries that follow are not necessarily identical to those submitted for the meeting. In some cases, the authors have corrected or expanded abstracts; and summaries of contributed papers commonly have been shortened.

II. REPORTS AT MEETINGS

Fourth International Symposium on Light Medium Mass Nuclei
University of Kansas, Lawrence, Kansas, 12—14 October 1970

LIFETIMES OF BOUND STATES

R. E. Segel

Electromagnetic transitions between low-lying states in the $20 \leq A \leq 40$ region have been surveyed. Omitting isospin-forbidden and/or isospin-unfavored transitions, it was found that E1 transitions are on the average inhibited by a factor of several thousand relative to single-particle speed. An average M1 transition proceeds at a few percent of single-particle speed, though some occur as fast as single-particle speed. E2 and E3 transitions are generally enhanced. It was found that M2 transitions do not show the inhibition that is present when such transitions occur in heavier nuclei. Four M3 transitions have been identified; two of these are enhanced.

In the region $19 \leq A \leq 26$, the rigid-rotator model works very well and relative transition rates are accurately predicted. An exception appears to be ^{23}Na, and it is speculated that this discrepancy may be due to experimental error. There is definitive evidence that the rigid rotator does not do a good job in predicting transition rates over the remainder of the sd shell. At the high end of the shell, the spherical shell model has had some success. Recent results obtained at Argonne show that the relative transition rates among states in the

"$(\pi d_{3/2})^{-1}(\nu f_{7/2})$" quartet do not fit the model within a factor of 2, even when effective moments are used. This result is in contrast to the success of the model in connecting the spectrum of ^{40}K with that of ^{38}Cl through the Pandya transformation. It is thus concluded that effective moments and effective charges cannot be expected to predict transition rates to better than a factor of 2.

Division of Nuclear Physics, American Physical Society

Houston, Texas, 15—17 October 1970

ELASTIC AND INELASTIC SCATTERING OF ^{14}N, ^{15}N, AND ^{16}O FROM ^{28}Si

K. O. Groeneveld,* A. Richter,† R. H. Siemssen, and G. Stoppenhagen

Bull. Am. Phys. Soc. 15, 1676-1677 (1970)

In order to study the influence of the projectiles on the inelastic heavy-ion scattering, the elastic and inelastic scattering of ^{14}N, ^{15}N, and ^{16}O from ^{28}Si have been measured at incident energies E(^{14}N) = 40 and 48 MeV, E(^{15}N) = 40.95 and 49.3 MeV, and E(^{16}O) = 40 and 55 MeV. Angular distributions for angles between 15° and 100° were obtained for the elastic scattering and between 35° and 100° for inelastic scattering to the 2^{+} (^{14,15}N, ^{16}O) and the 4^{+} (^{15}N, ^{16}O) levels in ^{28}Si. For each of the systems studied, well-developed diffraction patterns are found for the elastic and 2^{+} inelastic angular distributions at the higher of the two incident energies. The data are being subjected to optical-model and coupled-channel calculations.

*On leave of absence from the Institut für Kernphysik der Universität, Frankfurt, Germany.

†On leave of absence from the Max-Planck-Institut für Kernphysik, Heidelberg, Germany.

FURTHER[1] DEVELOPMENTS IN THE ENERGY-LEVEL STATISTIC Λ(n)

J. E. Monahan and N. Rosenzweig

Bull. Am. Phys. Soc. 15, 1668 (1970)

A convenient method has been devised for computing all the values of Λ(n) which arise in a "single" series of N energy levels. The value of Λ(n) averaged with respect to all possible sub-sequences of n successive spacings provides an empirical estimate Λ^{*}(n) of the

[1] J. E. Monahan and N. Rosenzweig, Phys. Rev. C1, 1714 (1970).

ensemble average $\langle \Lambda(n) \rangle$ of Ref. 1. The quantity $\langle [\Lambda^*(n) - \langle \Lambda(n) \rangle]^2 \rangle$ is small if $n \ll N$ and its value depends also on the correlation between spacings. A calculation of $\Lambda^*(n)$ based on the neutron-capture data for ^{166}Er obtained recently[2] at the Columbia Nevis synchro-cyclotron reveals the sharp decrease of $\langle \Lambda(n) \rangle$ as n increases from 1 to 10, as predicted by the random-matrix model.[1] For large n, $\Lambda^*(n)$ viewed as a function of the mean spacing D has a sharp minimum in the neighborhood of the arithmetic mean.

[2] L. J. Rainwater, private communication.

A STUDY OF THE γ DECAY OF ^{47}Ti BY USE OF THE ^{45}Sc(^{3}He,pγ)^{47}Ti REACTION

L. Meyer-Schützmeister, J. W. Smith, G. Hardie,* and H. Siefken†

Bull. Am. Phys. Soc. 15, 1673 (1970)

The γ decay of several levels in ^{47}Ti has been studied with the ^{45}Sc(^{3}He,pγ)^{47}Ti reaction induced by the 17-MeV ^{3}He beam from the Argonne tandem accelerator. By detecting the gammas in a large Ge(Li) detector in coincidence with protons at 0°, we were able to observe the γ decay of the ^{47}Ti states that were strongly populated with orbital-angular-momentum transfer $L_{np} = 0$. Some of these levels decay strongly to lower lying states, whose γ decay was also studied. Thus we have measured the γ decay of the levels at 7.370 MeV (isobaric analog), 3.220, 2.835, 2.612, 1.447, and 1.249 MeV. Since either the cross sections for populating the levels by the (^{3}He,p) reaction are small (namely 22, 57, and 33 μb/sr at 7° to the incoming beam for the 2.612-, 2.835-, and 3.220-MeV levels, respectively) or the γ decay is fragmented (as it is for the 7.37-MeV state with σ = 390 μb/sr

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†Greenville College, Greenville, Illinois.

at 7^{o}), the measured γ spectra (except those from the 1.249- and 1.447-MeV states) suffer from low counting rates.

Within our statistical error, which might amount to 10—15% of the total γ decay for each of the states, we observed no direct ground-state transitions except from the 2.835-MeV state. Instead, transitions to the first excited state at 159 keV were observed from all levels, with the possible exception of the 3.220-MeV level. The complexity of the γ decay of the analog state at 7.37 MeV indicates that the strong M1 transition to the state with the same nucleon configuration but lower T is absent—though such a transition is observed in the sd-shell nuclei.

Most of the studied states show large spectroscopic factors for single-nucleon transfer reactions, and it is likely that these can be described by rather simple nucleon configurations. For this reason, the γ decay of these levels can be investigated theoretically. We are in the process of comparing such calculations with our results.

IDENTIFICATION AND DISTORTED-WAVE ANALYSIS OF UNNATURAL-PARITY STATES IN ^{58}Ni

M. M. Stautberg
Bull. Am. Phys. Soc. 15, 1681 (1970)

The 2.900 (1), 3.414 (3), and 3.773 (3) MeV inelastic proton angular distributions[1] of ^{58}Ni were analyzed with DW theory, and are best characterized by L = 2, L = 2 + 4, and L = 2 distorted-wave curves, respectively. The known values[2] of J are shown in parentheses. Since the L transfer is even, these states have positive parity. The microscopic distorted-wave analysis using Hamada-Johnston and Gaussian realistic interactions was carried out with the wave

[1] O. N. Jarvis et al., Nucl. Phys. A102, 625 (1967).

[2] D. M. VanPatter et al., Nucl. Phys. A137, 353 (1969).

functions of Auerbach.[3] The smallness of the predicted cross sections (only ~0.1% of the experimental values) shows the necessity of including core effects. In the distorted-wave calculations for the 3^+ states, the L = 4 contribution is larger than the L = 2 contribution. Antisymmetrization was included in an approximate way with a δ-function pseudopotential. The average ratios σ_E/σ_{direct} are 0.8, 1.6, and 2.6 for L = 0, 2, and 4, respectively.

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[3] N. Auerbach, Phys. Rev. 163, 1203 (1967).

17th National Vacuum Symposium, Surface Science

Washington, D. C., 20—23 October 1970

HIGH-ENERGY ION-IMPACT PHENOMENA

M. Kaminsky

Journal of Vacuum Science and Technology

Energetic (MeV) ions penetrating through solids undergo certain primary processes (e.g., energy loss and charge exchange) and cause various secondary phenomena (e.g., sputtering, secondary-electron emission, and x-ray emission). In an amorphous solid the projectile will change its direction in successive collisions randomly; in a monocrystalline solid the projectile can be guided by the regular lattice arrangement, e.g., through the spaces between the planes (planar channeling) or along channels formed by parallel rows of atoms (axial channeling). In such cases the impact parameters of successive collisions can become correlated and their distribution is not random. Such directional effects ("channeling" effects) can in turn affect certain primary and secondary processes. The experimental and theoretical studies of some of these processes (e.g., ion ranges, backscattering of primary ions, energy loss, x-ray emission, radiation damage, and nuclear reactions) have been reviewed recently.[1—3]

The influence of channeling on the energy loss and on the yields of sputtering and secondary-electron emission is illustrated in Fig. 1. In this case protons are incident normal to different crystallographic planes of copper monocrystals. The angular spread of the incident proton beam was $<0.01^\circ$ and the angle of incidence was defined to $<0.1^\circ$. The energy loss of protons penetrating through thin monocrystalline copper foils was measured for proton energies ranging

[1] R. S. Nelson, The Observation of Atomic Collisions in Crystalline Solids (North-Holland Publishing Company, Amsterdam, 1968).

[2] G. Carter and J. S. Colligon, Ion Bombardments of Solids (American Elsevier Publishing Company, New York, 1968).

[3] S. Datz, C. Erginsoy, G. Leibfried, and H. O. Lutz, Ann. Rev. Nucl. Sci. 17, 129 (1967).

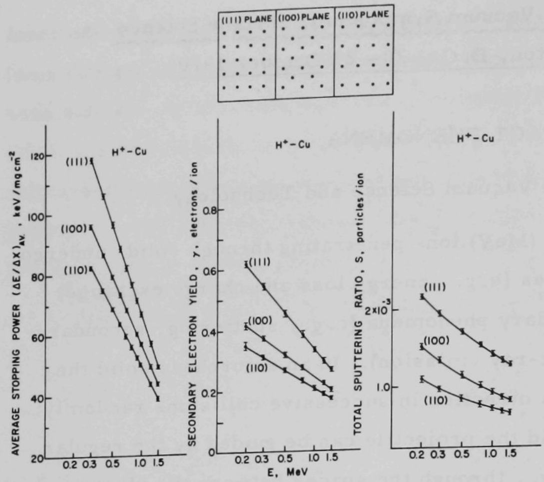

Fig. 1. The mean stopping power, the total secondary-electron yield, and the total sputtering yield when protons (incident with energy E) penetrate through copper monocrystals with their surfaces parallel to the indicated crystal planes.

from 0.30—1.50 MeV. Over twice the area struck by the beam, each foil thickness varied by $\lesssim 3\%$. The protons emerging from the foils were collimated before being analyzed with a surface-barrier solid-state detector. The experimental arrangement to measure the energy loss and the secondary-particle yields has been described previously.[4]

One notices in Fig. 1 that the energy-loss rate and the secondary-particle yields decrease in the order [111] > [100] > [110], which is the same order in which the transparency of the lattice along the respective directions becomes larger. The results suggest that the production mechanism of internal secondary particles has a strong influence on the observed orientation dependence of the yields. To gain further insight into the processes that slow down an ion penetrating a monocrystalline solid, charge-transfer processes have been studied by

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[4] M. Kaminsky, in Recent Developments in Mass Spectroscopy, Proceedings of the International Conference on Mass Spectroscopy, Kyoto, 8—12 September 1969, edited by K. Ogata and T. Hayakawa (University Park Press, Baltimore/Tokyo, 1970), pp. 1167-1172; Advan. Mass Spectrometry 3, 69 (1966); Phys. Rev. 126, 1267 (1962).

several authors.[5] For example, in the experiments described by Kaminsky,[5] deuterium particles emerging from monocrystalline Ni(110) or polycrystalline Ni foils with energies ranging from 90 to 800 keV were electrostatically analyzed according to their charge state and the ratio R(emergent beam) = $D^0/(D^0 + D^+)$ was determined. The observation that the R values for the monocrystalline foil were substantially lower than for the polycrystalline foil suggests a lower electron-capture probability for ions traversing and escaping from regions of lower electron density (e.g., the centers of lattice channels).

Certain secondary phenomena induced by energetic-ion impact on polycrystalline materials may play an important role in the erosion of satellite surfaces, of accelerator components, and of the vacuum walls of thermonuclear fusion reactors.

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[5] For example, S. Datz, T. S. Noggle, and C. D. Moak, Nucl. Instr. Methods 38, 221 (1965); H. O. Lutz, S. Datz, C. D. Moak, T. S. Noggle, and L. C. Northcliff, Bull. Am. Phys. Soc. 11, 177 (1969); F. W. Martin, Phys. Rev. Letters 22, 329 (1969); M. Kaminsky, Bull. Am. Phys. Soc. 14, 846 (1969).

Division of Plasma Physics, American Physical Society

Washington, D. C., 4—7 November 1970

RADIOFREQUENCY CONFINEMENT AND STOCHASTIC HEATING OF PLASMAS

Albert J. Hatch

Bull. Am. Phys. Soc. 15, 1407 (1970)

Radiofrequency confinement of electrons in a low-density plasma is usually treated in terms of a quasi-potential Φ which represents the period-averaged energy of an electron oscillating collisionlessly in an rf field. Elastic collisions between electrons and neutral gas molecules in an rf field result in stochastic heating of the former, the average energy gain per collision being twice the period-averaged oscillatory energy. For any finite electron-neutral collision frequency, one possible adverse effect of stochastic heating on rf confinement is that the energy of an electron may be increased to twice the depth of the Φ well in a time as short as the collision period. Another possible effect is that ionization (gaseous breakdown) may occur in the vicinity of the Φ well. Another is that the resulting ionization may cause a serious alteration of the field that establishes the Φ well. Any one of these effects appears to preclude steady-state rf confinement of plasmas.

Division of Electron and Atomic Physics, American Physical Society

Seattle, 23—25 November 1970

HYPERFINE STRUCTURE OF ^{143,145}Nd

W. J. Childs

Bull. Am. Phys. Soc. 15, 1521 (1970)

Spalding's atomic-beam magnetic-resonance work[1] on the hfs of the lowest term ($4f^4 6s^2$ ^5I) of ^{143,145}Nd is being refined and extended to include all states of the multiplet. The listed hyperfine-interaction constants A and B and g factors g_J will be compared with the theory. The uncertainties given are two standard deviations. The results will be compared with predictions based on Conway's eigenvectors for the states.

Isotope	J	A (MHz)	B (MHz)	g_J
^{143}Nd	4	-195.652(2)	122.608(34)	0.60329(4)
	5	-153.679(2)	115.741(36)	0.90047(6)
	6	-130.611(2)	119.284(46)	1.06990(4)
	7	-117.604(2)	129.281(48)	1.17537(4)
	8	-110.4 ± 0.2	141.9 ± 6.2	1.24521(10)[a]
^{145}Nd	4	-121.628(2)	64.637(28)	
	5	-95.535(2)	61.044(42)	
	6	-81.195(2)	62.926(58)	
	7	-73.108(2)	68.165(74)	

[a] Measured in ^{144}Nd.

[1] I. J. Spalding, Proc. Phys. Soc. (London) 81, 156 (1963).

LANDÉ g FACTOR OF ^{254}Fm

L. S. Goodman, H. Diamond,* H. E. Stanton, and M. S. Fred*

Bull. Am. Phys. Soc. 15, 1521 (1970)

The atomic-beam magnetic-resonance method has been used to measure the Landé g factor of fermium in its atomic ground state. The experimental value $g = 1.16052 \pm 0.00014$ is in good agreement with the value 1.163 calculated for the $^3H_6$ level of the configuration $5f^{12}7s^2$ by use of extrapolated parameters. The g value is near the LS limit 1.167 because the only other $J = 6$ level of the configuration is 30 000 cm^{-1} above the ground state. A new atomic-beam instrument allowed detection of transmitted alpha-particle radioactivity from 5×10^{-9}-g charges of 3.24-h ^{254}Fm. A beam of zero-valent fermium atoms was obtained by heating FmF_3 and its HoF_3 carrier in the presence of zirconium carbide and tungsten.

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*Chemistry Division.

Division of Nuclear Physics, American Physical Society

New Orleans, 23—25 November 1970

REACTION SYMMETRIES FOR ISOSPIN-MULTIPLET PRODUCTION

A. Richter*

Bull. Am. Phys. Soc. 15, 1317 (1970)

Consider a reaction of the type a + b $\leftrightarrow$ c + c' in which the initial states a, b have definite channel-isospin parity $\pi_T = (-)^T$, the isospin parity is conserved throughout the reaction, and c and c' are members of the same isospin multiplet and obey the usual ladder-operator relations. In such a case the Barshay-Temmer theorem predicts that the angular distributions of the reaction products c and c' will be symmetric about 90° in the c.m. system. This theorem has been tested experimentally at several laboratories for reactions involving the fermion doublets ^{3}He-t, ^{7}Be-^{7}Li, and ^{13}N-^{13}C in the reactions α(d,t)^{3}He, ^{10}B(α,^{7}Li)^{7}Be, and ^{12}C(^{14}N,^{13}C)^{13}N, respectively. The predicted symmetry was observed in the second and third of these reactions while the first shows sizable charge-asymmetry effects at higher energies. The theorem and its experimental tests will be discussed together with the implication of their results. Possible violations of reaction symmetries are considered. In the example of the reaction α(d,t)^{3}He, it is shown that the effect of Coulomb forces must be estimated before observed asymmetries can be used to decide for or against the existence of isospin-violating nuclear forces. This is done in the specific example in terms of a simple distorted-wave Born approximation. Elastic scattering, multiparticle production in the final state, and symmetry relations for polarizations are also noted. Finally, the theorem will be extended to apply to the reaction symmetries for any multiplet production.

This will be a brief review of our present understanding of symmetry relations in nuclear reactions involving the production of isospin multiplets. Studies of such symmetry relations are still in an early stage, but they are extremely useful and rewarding in understanding effects of isospin symmetry breaking in reaction mechanisms and in spectroscopy involving complex nuclei. Hence they complement the

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*Present address: Max-Planck-Institut für Kernphysik, Heidelberg. The work reported here was done while on leave of absence at Argonne.

various other means of exploring the full role of isospin in nuclear physics.[1]

The talk will be divided into five sections. We first note the existence of symmetry relations in reactions of the type $a + b \rightleftarrows c + c'$, and remark on the Barshay-Temmer isospin theorem[2] and its implications.[3] Section II contains the experimental evidence for those symmetry relations and a detailed discussion of the production of the isospin fermion doublets $^{13}C_{g.s.}$ - $^{13}N_{g.s.}$, $^{7}Li_{g.s.}$ - $^{7}Be_{g.s.}$, and $^{7}Li_{1st}$ - $^{7}Be_{1st}$. In Section III we consider possible symmetry violations and emphasize the experimental evidence for isospin-breaking effects in the production of the mass-3 fermion doublet $T_{g.s.}$ - $^{3}He_{g.s.}$. In Section IV we treat those charge-asymmetry effects in a simple model based on the distorted-wave Born approximation. Finally (Section V), we note the existence of general symmetry relations for any multiplet production.

The experiments discussed here, which were performed at Argonne, result from a collaboration with H. T. Fortune and B. Zeidman; the theoretical aspects of the problems were studied in collaboration with C. M. Vincent and with D. Robson from The Florida State University. I am very much indebted to all of my collaborators.

I. Symmetry Relations for Isospin-Multiplet Production

Consider the two-body nuclear reaction $a + b \rightarrow c + c'$ or its inverse. If the product nuclei c and c' are members of the same isospin multiplet, if the initial state a + b has a definite channel-isospin parity $\pi_T = (-)^T$, where T is even or odd only, and if the isospin parity is conserved throughout the reaction, then the angular

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[1] See, for example, Isospin in Nuclear Physics, edited by D. H. Wilkinson (North-Holland Publishing Company, Amsterdam, 1970).

[2] S. Barshay and G. M. Temmer, Phys. Rev. Letters 12, 728 (1964).

[3] D. Robson and A. Richter, Ann. Phys. (N. Y.), in press.

distributions for the reaction products c and c' will be symmetric about 90° in the c.m. system. That is,

$$d\sigma_c(\theta)/d\omega = d\sigma_c(\pi-\theta)/d\omega , \tag{1}$$

$$d\sigma_{c'}(\theta)/d\omega = d\sigma_{c'}(\pi-\theta)/d\omega . \tag{2}$$

(This theorem was noted explicitly by Barshay and Temmer[2] in 1964 but was implicit in certain earlier papers, e.g., in one by Peshkin[4] in 1961. Robson and the author[3] have recently proved it in several ways and generalized it.) The condition of definite channel isospin in the initial channel can be achieved if the isospin of either particle a or particle b is zero, but the channel-isospin parity is also definite when a and b are two like charge states[5,6] with $T = |T_z|$, i.e., when both a and b have either components $T_{za}, T_{zb} > 0$ or $T_{za}, T_{zb} < 0$.

For practical purposes it is useful to restate the symmetry theorem. Instead of requiring fore-and-aft symmetry for the production of either c or c', we use the purely kinematic relation

$$d\sigma_c(\theta)/d\omega = d\sigma_{c'}(\pi-\theta)/d\omega \tag{3}$$

and require that at a fixed scattering angle θ, the transition rates leading to the production of c and c' have to be equal, i.e.,

$$[d\sigma_c(\theta)/d\omega]/[d\sigma_{c'}(\theta)/d\omega] = 1. \tag{4}$$

In fact, almost all experiments performed to date use this relation instead of testing the symmetry of $d\sigma_c(\theta)$ or $d\sigma_{c'}(\theta)$ by measuring it between 0 and π. The experimental advantage is that detecting particles c and c' simultaneously with the same detecting system considerably reduces the experimental errors resulting from uncertainties in the

[4] M. Peshkin, Phys. Rev. 121, 636 (1961).

[5] W. von Oertzen, Z. Physik 228, 182 (1969).

[6] S. M. Bilenkii, L. I. Lapidus, R. M. Ryndin, and L. Sh. Shekhter, Soviet J. Nucl. Phys. 4, 763 (1967).

scattering angle and solid angle, problems of detector efficiency, and the like. Avoiding these errors, which otherwise would show up in a comparison of absolute cross sections, makes a high-precision experiment possible.

Symmetry relations for polarization P and for higher rank tensor characteristics of reactions of the type $a + b \rightleftarrows c + c'$ can also be obtained. As in deriving the Barshay-Temmer theorem, Eqs. (1) and (2), the requirements are (1) that c and c' belong to the same isospin multiplet, (2) that the channel-isospin parity π_T is odd or even only, and (3) that π_T is conserved in the reaction; and an additional requirement is that the spins of c and c' are nonzero. Under these conditions, it follows that

$$P_c(\theta) = -P_c(\pi-\theta), \quad (5)$$

$$P_{c'}(\theta) = -P_{c'}(\pi-\theta). \quad (6)$$

These polarization relations[6] are included for completeness only.

II. Experimental Production of ^{13}C-^{13}N and ^{7}Li-^{7}Be Multiplets

To date, only three measurements of differential cross sections have been made to test the Barshay-Temmer theorem. Two of these will now be discussed.

The mass-13 ground-state doublet was studied by von Oertzen _et al._[7] in the reaction

$$^{12}C + {}^{14}N \rightarrow {}^{13}C_{g.s.} + {}^{13}N_{g.s.}, \quad (7)$$

with the initial system $^{12}C + {}^{14}N$ prepared in a T=0 state. The angular distributions (upper half of Fig. 2) for the production of $^{13}C_{g.s.}$ and $^{13}N_{g.s.}$ are virtually the same (within the error bars) out to scattering angles $\theta_{c.m.} \approx 30^{\circ}$. The ratio $\sigma(^{13}C)/\sigma(^{13}N)$ is unity (lower half of

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[7] W. von Oertzen, J. C. Jaqmart, M. Liu, F. Pougheon, J. C. Roynette, and M. Riou, Phys. Letters 28B, 482 (1969); Nucl. Phys. A143, 34 (1970).

figure) and hence compatible with the predictions of the theorem. This result confirms three things. First, the states of the mass-13 ground-state doublet are very true mirror states, i.e., they are connected by a simple rotation in isospin space. Second, and this is closely connected to the first point and emerges from a model calculation, the difference between the wave functions of the transferred neutron and proton in the mirror nuclei ^{13}C and ^{13}N is smaller than 0.8% at an interaction radius ($r \approx 1.65\ A^{1/3}$) characteristic for a heavy-ion transfer reaction. And third, the Coulomb interaction, which is of course isospin symmetry breaking, seems to play a negligible role in the transfer of the proton at energies well above the Coulomb barrier.

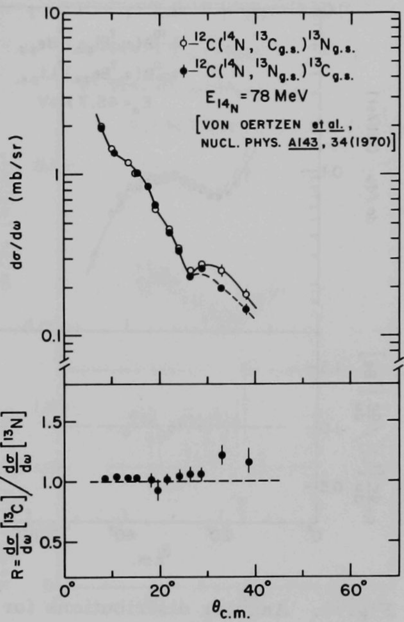

Fig. 2. Results of the experiment of von Oertzen et al. (Ref. 7b) on the mass-13 ground-state doublet. The upper graphs show the differential cross sections for the indicated reactions, the lower one is a plot of the ratios of these cross sections.

This experiment used a magnet and did not record the product nuclei ^{13}C and ^{13}N simultaneously. At the same time, we studied the Barshay-Temmer theorem for the isospin doublets of the mass-7 ground state and first excited state via the reactions

$$^{10}B + \alpha \rightarrow {}^{7}Li_{g.s.} + {}^{7}Be_{g.s.}, \qquad Q = -16.2 \text{ MeV}, \tag{8}$$

$$T: \quad 0 \quad 0 \quad \tfrac{1}{2} \qquad \tfrac{1}{2}$$

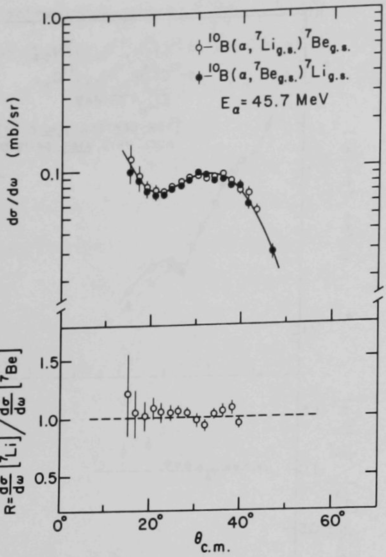

Fig. 3. Angular distributions for the ground-state $^{10}B + \alpha$ reactions leading to the mass-7 doublet. The differential cross sections are shown in the upper curves, the ratio of cross sections in the lower.

and

$$^{10}B + \alpha \rightarrow {}^{7}Li_{0.48} + {}^{7}Be_{0.43}, \tag{9}$$

induced by 45.7-MeV alpha particles.[8] The product nuclei from both reactions were detected simultaneously with the same solid-state counter telescope. Particles were identified via a pulse-multiplier $(dE/dx) \cdot E$ system.

The angular distributions for the ground-state transitions, taken in 1° steps from 8° to 23° in the laboratory system, are shown in Fig. 3. In the upper part of the figure, the differential cross section $d\sigma/d\omega$ in mb/sr has been plotted as a function of scattering angle. Filled and open circles correspond to the two ground-state transitions. The shapes and magnitudes of the two angular distributions are almost identical within the experimental errors, which result mainly from counting statistics and from background subtraction. Even though the absolute cross section given is uncertain to about 20%, this uncertainty is not present in the measurement of relative cross sections. The ratio between the cross sections for the two g. s. transitions has been plotted in the lower part of this figure. There are no sizable departures of this ratio from unity, though

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[8] H. T. Fortune, A. Richter, and B. Zeidman, Phys. Letters 30B, 175 (1969).

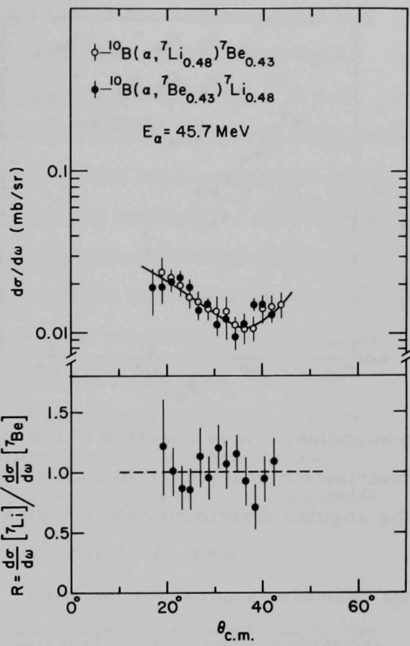

Fig. 4. Same as Fig. 3 except that the data are for the production of the mass-7 doublet in the first excited state.

slightly more ^7Li seems to be produced. We note that the shape of the angular distribution is typical of a direct reaction.

Much as for the g. s. transitions, we also observed symmetry about 90° (or equality for c and c' as expected from the equivalent formulation of the theorem) of the angular distributions for producing the first-excited-state doublet in the mass-7 system. Figure 4 compares the two cross sections, which are fairly low and were difficult to measure and hence are quite uncertain. It is worth noting that the behavior of the angular distribution going to $\frac{1}{2}^-$ states is distinctly different from that of transitions to the $\frac{3}{2}^-$ ground state. We conclude from those results that, as in the case for the production of the mass-13 ground-state isospin doublets, the symmetry of the angular distributions theoretically predicted is nearly confirmed; the slight asymmetry for the g. s. transitions is most likely due to the isospin-symmetry-breaking Coulomb interaction. (The importance of such effects will be explained in detail in Sec. IV.) We also have evidence that the observed symmetry in the angular distributions is due to no other reasons than the ones stated in conjunction with the theorem—namely the definite isospin-channel parity and the fact that the product nuclei belong to the same isobaric multiplet. A

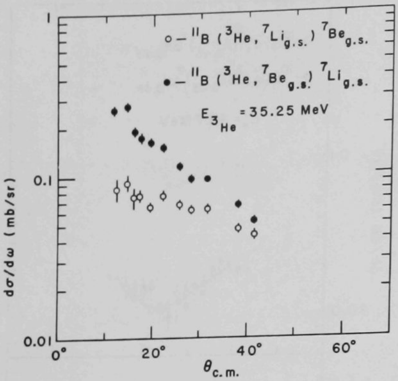

Fig. 5. Angular distributions for the ground-state ${}^{11}B + {}^3He$ reactions leading to the mass-7 doublet.

compound-nucleus reaction which would lead to a symmetric angular distribution under certain conditions is unlikely because the shapes of the angular distributions are typical of a direct reaction.

With 35.3-MeV ${}^3He$ particles from the Argonne cyclotron, we have also studied the reaction

$$ {}^{11}B + {}^{3}He \rightarrow {}^{7}Li_{g.s.} + {}^{7}Be_{g.s.}, \qquad Q = -7.1 \text{ MeV}, \tag{10}$$

$$ T: \quad \tfrac{1}{2} \quad \tfrac{1}{2} \qquad \tfrac{1}{2} \qquad \tfrac{1}{2} $$

in which the channel-isospin parity is not definite in the entrance channel because of $T_i = 0, 1$. Figure 5 shows the angular distributions for the mirror transitions; there is absolutely no equality of the cross sections.

The reaction ${}^{12}C + d \rightarrow {}^7Li_{g.s.} + {}^7Be_{g.s.}$ has just been measured at $E_d = 39.1$ MeV as a test of the Barshay-Temmer theorem. Preliminary analysis indicates that the ratio $R = [d\sigma({}^7Li)/d\omega]/[d\sigma({}^7Be)/d\omega]$ is unity except at forward angles, where more ${}^7Li$ seems to be produced. The data seem to follow the same trend as that reported for the reaction ${}^{10}B + \alpha \rightarrow {}^7Li_{g.s.} + {}^7Be_{g.s.}$ (J. C. Young, private communication). One interesting aspect of this result is that if any isospin violation in the deuteron is caused by a polarization of the n-p pair in the Coulomb field of ${}^{12}C$, this violation is small—in essential agreement with a quantitative prediction by Drachmann [Phys. Rev. Letters 17, 1017 (1966)]. A T=1 isospin impurity in the deuteron ground state would have resulted in a nondefinite channel-isospin parity in the $^{12}C + d$ channel and would have caused asymmetries in the angular distributions.

Having collected evidence for the near symmetry in the production of the mass-13 and mass-7 isospin multiplets, and having given arguments that this symmetry is connected to isospin invariance and not due to overriding reasons, we conclude that the ground state of ^{13}C and ^{13}N, of ^{7}Li and ^{7}Be, and of the first excited states of ^{7}Li and ^{7}Be constitute true isospin doublets, i.e., they are truly identical except for their total charge number. Furthermore, it is concluded that the interaction causing the transition conserves isospin also. Those statements are not always true, however, as will be discussed next.

III. Isospin Violations and Evidence from the Production of the Multiplet T-^{3}He

There are four basic groups of isospin violations[3] leading to angular distributions that are asymmetric about 90° (or unequal for c and c'), namely (1) violations in the isospin of particle a, (2) violations in the isospin of particle b, (3) violations in the interaction operator, and (4) violations in the isospin and multiplet nature of particles c and c'. A lack of isospin purity in the ground states of particles a and b may result in asymmetries about 90° because the isospin-channel parity is then indefinite. Furthermore, any violation of fore-aft symmetry will be angle dependent. To treat the violations in the interaction operator, this operator is customarily split into a direct and a compound-nucleus part. Even then, it is difficult to treat the violations due to these two parts.[9] There are finally violations of the

[9] A well-known exception occurs, however, if the compound-nucleus part is dominant and can be treated within the Hauser-Feshbach statistical type of approach. In this situation, average cross sections will

isospin of the multiplet members c and c'. These violations appear to play a unique role since they destroy the basic symmetry relation between amplitudes, in which oddness or evenness about $\theta = \pi/2$ is related to the isospin-channel parity in the outgoing channels. Experimentally those different groups of violations, which could occur simultaneously, of course, usually are difficult to disentangle in terms of observed asymmetries. Despite these difficulties, we will next discuss evidence for the existence of violations of the types (3) and (4) in the production of the isodoublet T-^{3}He.

Before turning to this matter, let us remark on the technical problem of defining asymmetries. In the earlier discussion, asymmetries were defined in terms of cross-section ratios, which have the disadvantage of not being conveniently normalized. For the case of complete angular distributions, we now adopt the more appealing definition

$$W(\theta) = [\sigma(\theta) - \sigma(\pi-\theta)]/[\sigma(\theta) + \sigma(\pi-\theta)], \tag{11}$$

where σ is the differential cross section for either outgoing particle in $a + b \rightleftarrows c + c'$ and the detectors are set at the conjugate angles θ and $\pi-\theta$. For the case in which particles c and c' are measured at the same scattering angle, we have analogously

$$W(\theta) = [\sigma_c(\theta) - \sigma_{c'}(\theta)]/[\sigma_c(\theta) + \sigma_{c'}(\theta)]. \tag{12}$$

And from the kinematical relation $\sigma_c(\theta) = \sigma_{c'}(\pi-\theta)$ we immediately get

$$W(\theta) = -W(\pi-\theta), \tag{13}$$

which states that the antisymmetry of $W(\theta)$ about $\theta = \pi/2$ is true for

involve incoherent contributions from states of opposite parity and will therefore exhibit symmetry about $\pi/2$ independently of isospin considerations. More generally, symmetry about $\pi/2$ occurs if the reaction amplitude involves only one parity or if the amplitudes for each parity are $\pi/2$ out of phase. The interest here, however, is in explaining deviations from symmetry about $\pi/2$.

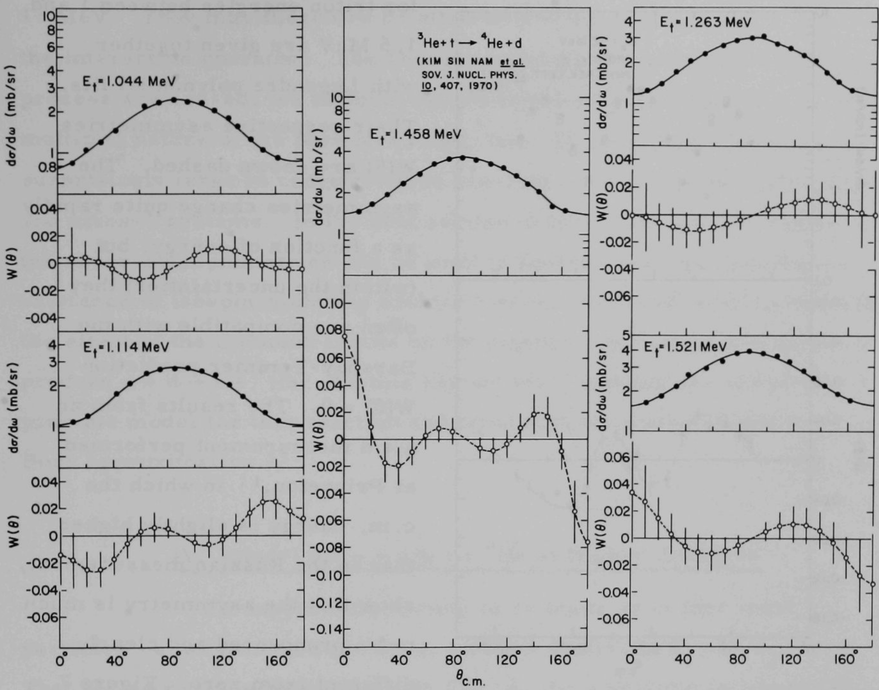

Fig. 6. Angular distributions and asymmetries W(θ) of the deuterons from the $^3He(t,d)^4He$ reaction induced by tritons with energies between 1 and 1.5 MeV. The curves are Legendre-polynomial fits. The data are from Ref. 10.

any nuclear reaction $a + b \rightleftarrows c + c'$—independent of multiplet production. In order to have a phase convention, we let[3] particle c be chosen such that $T_{zc} > T_{zc'}$, with the low-energy convention $t_z = +\frac{1}{2}$ for neutrons. (However, some of the figures to be shown later were prepared on the basis of the reverse convention $T_{zc} < T_{zc'}$.)

Evidence that the symmetry predicted by the Barshay-Temmer theorem may be broken is found in studies of the $^3He + t \rightleftarrows \alpha + d$ reaction. In Fig. 6, which displays the results from an accurate Russian experiment,[10] angular distributions of the deuterons from $^3He(t,d)^4He$

[10] Kim San Nam, G. M. Osetinskii, and V. A. Sergeev, Soviet J. Nucl. Phys. 10, 407 (1970).

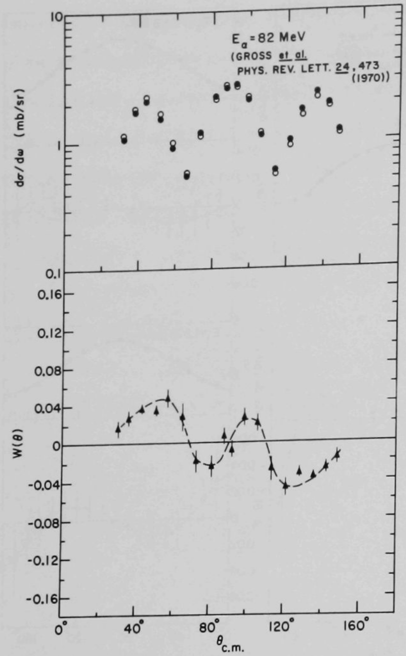

Fig. 7. Angular distributions and asymmetries from the $\alpha + d$ reactions. The data are from Oak Ridge (Ref. 12).

for triton energies between 1 and 1.5 MeV are given together with Legendre polynomial fits. Their respective asymmetries $W(\theta)$ are shown dashed. The asymmetries change quite rapidly as a function of energy, but (within the uncertainties) they often are compatible with the Barshay-Temmer prediction $W(\theta) = 0$. The results from an $\alpha + d$ measurement performed at Princeton,[11] in which the c.m. energy is slightly higher than in the Russian measurement, show that the asymmetry is much more pronounced and clearly different from zero. Figure 7 shows measurements from Oak Ridge[12] at even higher energies (E_α = 82 MeV). The angular distributions for the outgoing ^{3}He and t have clearly developed into a pattern characteristic of a direct reaction, and the asymmetry is sizable.

The charge asymmetries revealed in the experiments at the lower energies most likely are predominantly due to isospin mixing in the compound nucleus ^{6}Li, which is excited only to about

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[11] G. J. Wagner, C. Foster, and B. Greenebaum, private communication. I thank Dr. Wagner for allowing me to report this result prior to publication.

[12] E. E. Gross, E. Newman, W. J. Roberts, R. W. Rutkowski, and A. Zucker, Phys. Rev. Letters 24, 468 (1970).

17 MeV. They may therefore be attributed to the group of violations in the interaction operator. The charge asymmetries in the high-energy process are caused, we believe, by violations in the isospin and multiplet nature of the particles t and ^{3}He. The asymmetries are surprisingly large in comparison to previous results for the mass-13 and mass-7 systems. In the next section it will be shown that before the observed asymmetries can be used to decide for or against the existence of isospin-violating nuclear forces, it is necessary to estimate the effect of the Coulomb forces on the angular distribution of the process $\alpha + d \rightarrow t + {}^3He$. To this end we will construct the simplest possible model for this reaction and treat it in the distorted-wave Born approximation.[13]

IV. Model for $\alpha + d \leftrightarrows t + {}^3He$ at Higher Energies

We suppose the system to be made up of four inert particles: a neutron n, a proton p, and two deuterons d_1 and d_2. That is, as shown schematically in Fig. 8, the α particle is composed of a neutron, a proton, and a deuteron. The Hamiltonian of the model has the form

$$H = K + V_{np} + V_{nd_1} + V_{nd_2} + V_{pd_1} + V_{pd_2} + V_{d_1d_2}, \tag{14}$$

where K is the total kinetic energy.

Since d_1 and d_2 are identical, it is necessary to symmetrize the (d,t) transition amplitude with respect to all their coordinates. Thus

$$T_{dt} = T_{d_1t_1} + T_{d_1t_2}, \tag{15}$$

where $T_{d_1t_1}$ is the amplitude for the reaction in which d_1 is incident on α, and a triton containing d_1 is emitted in a certain direction. In the same way (Fig. 8), $T_{d_1t_2}$ is the amplitude for the reaction in which

[13] A. Richter and C. M. Vincent, Phys. Rev. Letters 25, 1460 (1970).

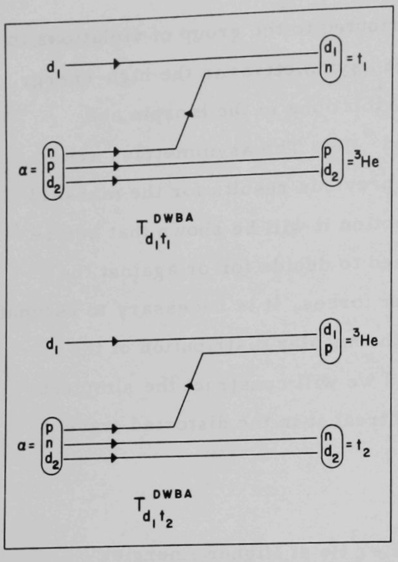

Fig. 8. Schematic diagram showing the meanings of the transition amplitudes $T^{DWBA}_{d_1 t_1}$ and $T^{DWBA}_{d_1 t_2}$.

d_1 is incident on α, and a triton containing d_2 is emitted in the same direction as before. We use the DWBA to evaluate $T_{d_1 t_1}$ and $T_{d_1 t_2}$ in zero range. The final result for T^{DWBA}_{dt} is

$$T^{DWBA}_{dt} = S_n^{1/2} D_{0\,n} \int d\vec{r}\, \chi_{d\alpha}(c\vec{r})\, F_n(\vec{r})\, \chi^{+}_{t\,{}^3He}(\vec{r})$$

$$+ S_p^{1/2} D_{0\,p} \int d\vec{r}\, \chi_{d\alpha}(c\vec{r})\, F_p(\vec{r})\, \chi^{+}_{t\,{}^3He}(-\vec{r}). \tag{16}$$

The transition amplitude consists of two terms involving spectroscopic factors, normalization factors, and form factors corresponding to the neutron and proton transfer. In addition, there are the normal distorted waves in the scattering channels. This expression is evaluated by expanding the distorted waves in partial waves. The indicated replacement of $\vec{r}$ by $-\vec{r}$ is then done by using the formula

$$\mathcal{Y}_{LM}(-\vec{r}) = (-)^L\, \mathcal{Y}_{LM}(\vec{r}), \tag{17}$$

where $\mathcal{Y}_{LM}$ is a solid harmonic of order L and L is the orbital angular momentum of the α particle. The transition matrix element, expressed as a linear combination of the overlap integrals, may be written

$$\bar{f} = f(d_1 t_1) + [(S_p{}^{1/2} D_{0\,p})/(S_n{}^{1/2} D_{0\,n})](-)^L f(d_1 t_2). \tag{18}$$

Since the differential cross section $d\sigma/d\omega$ is proportional to $|\bar{f}|^2$, there are interference terms between the two amplitudes, just as in the case of real identical particles.

While we can say little about the spectroscopic factors, the Coulomb force will certainly cause differences in the D_0's and the F's in Eq. (16). Following a suggestion of Thompson and Hering,[14] we calculated them by the separation-energy method. The form factors were represented by

$$F_n \rightarrow ({}^3\text{He} \oplus n) \rightarrow V^{\text{HULTHÉN}}(r), \tag{19}$$

$$F_p \rightarrow (t \oplus p) \rightarrow V^{\text{HULTHÉN}}(r) + V^{\text{COUL}}(r), \tag{20}$$

where $V^{\text{HULTHÉN}}$ and V^{COUL} are Hulthén and Coulomb potentials, respectively; and the normalization factors were taken to be

$$D_{0\,n} \rightarrow (d \oplus n) \rightarrow V^{\text{HULTHÉN}}(r) \rightarrow 159\ \text{MeV-F}^2, \tag{21}$$

$$D_{0\,p} \rightarrow (d \oplus p) \rightarrow V^{\text{HULTHÉN}}(r) + V^{\text{COUL}}(r) \rightarrow 145\ \text{MeV-F}^2. \tag{22}$$

The difference between F_n and F_p is quite small except at large distances; it rises to $\sim$7% at 10 F. It is not surprising that the Coulomb potential should have a larger effect on the D_0's. By a simple transformation one can write[15]

[14] W. J. Thompson and W. R. Hering, Phys. Rev. Letters 24, 272 (1970).

[15] An alternative representation for the finite-range normalization constants would be $D_{0\,n} = \int d\vec{r}\, V^{\text{NUC}}(r)\, \psi(r)$ and $D_{0\,p} = \int d\vec{r}\,[V^{\text{NUC}}(r) + V^{\text{COUL}}(r)]\, \psi(r)$, where V^{NUC} and V^{COUL} are the nuclear and the Coulomb potentials, respectively. Of course, the Coulomb potential is the only one that is effective at large distances where the nucleon tails of $(d \oplus n)$ and $(d \oplus p)$ are different.

$$D_0 = \epsilon \int dr\, \psi, \tag{23}$$

with $\epsilon_n = 6.258$ MeV and $\epsilon_p = 5.493$ MeV. The integral of the wave function is very similar for the charged and uncharged cases, since the perturbation of the wave function arises through the small off-diagonal elements of the Coulomb potential. In contrast, the separation energy ϵ is perturbed through a diagonal element of the Coulomb potential, and this is large.

Little will be said about the other ingredients for the calculations of the DWBA matrix element. Since the range of the dn and dp interactions is not well known relative to the size of the α particle, we corrected for finite-range effects by a method developed for Hulthén interactions. The distorted waves were calculated from Woods-Saxon potentials. Parameters for α + d scattering were reasonably well known, those for ^{3}He + t only poorly. It can be shown,[16] however, that the poor knowledge of the ^{3}He + t parameters does not make any great difference in the conclusions.

The effect and importance of interference is demonstrated in Fig. 9. The three curves correspond respectively to calculating the cross section with an unsymmetrized amplitude $|f(\theta)|^2$, to using $|f(\theta)|^2 + |f(\pi-\theta)|^2$, and to taking account of the interference terms properly. Only in the latter case does the correct pattern emerge, as can be seen in Fig. 10, which shows the results of a DWBA calculation.

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[16] In plane-wave stripping, the relative momentum component of a transferred nucleon relative to the triton or ^{3}He in the α particle at $E_\alpha = 82$ MeV is such that one is almost as close as is physically possible to the plane-wave pole for a Hulthén internal wave function. Therefore, from polology arguments, the distortion effects should be minimal at forward angles. [See J. P. F. Sellschop and D. W. Mingay, Proceedings of the Conference on Direct Interactions and Nuclear Reaction Mechanisms, Padua, 1962, edited by E. Clementel and C. Villi (Gordon and Breach, Science Publishers, New York/London, 1963), p. 425.] I am indebted to Dr. W. J. Thompson for pointing this out to me.

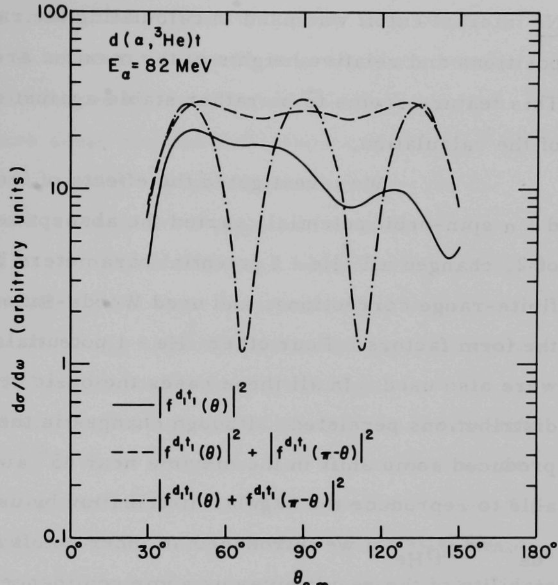

Fig. 9. Effect of interference in calculating the cross section.

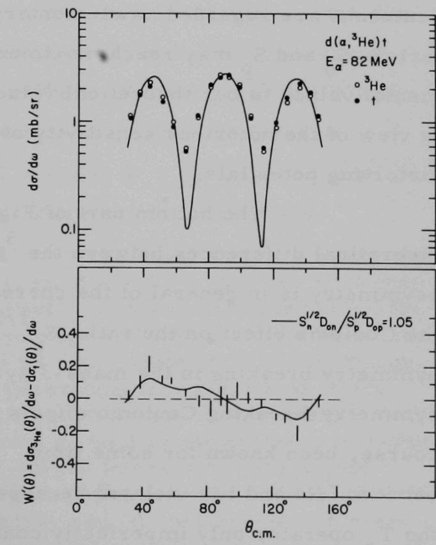

Fig. 10. Results for the $D(\alpha, {}^3He)T$ reaction at E_α = 82 MeV. The upper part shows the angular distribution together with a DWBA calculation with $(S_n^{1/2} D_{0\,n})/(S_p^{1/2} D_{0\,p}) = 1.05$. The lower plot shows the experimental values (points) and the theoretical prediction (curve) of the difference between the ^3He and t yields. The experimental points in this figure are taken from Fig. 1 of Ref. 12. The curve in the upper part corresponds to the detection of ^3He.

No internal cutoff was used in calculating the radial integrals. The positions and relative heights of the maxima are well reproduced. This feature seems to be rather stable against changes in the details of the calculation.

We investigated the effects of including a reasonable $d + \alpha$ spin-orbit potential, varied the absorptive potential by a factor of 2, changed all $^3He + t$ potential parameters by ±10%, omitted the finite-range corrections, and used Woods-Saxon potentials to generate the form factors. Four other $^3He + t$ potentials from the literature were also used. In all these cases the basic structure of the angular distributions persisted, although changes in the $^3He + t$ potentials produced some shift in the maxima near 45° and 135°. We were even able to reproduce the angular distribution by using plane waves for $\chi_{d\alpha}$ and χ_{t^3He} if we introduced an inner cutoff at about 3.5 F. The stability of the result gives us some confidence that the crudity of our calculation will not invalidate it.

In the present extreme cluster model, in which the deuterons are regarded as elementary particles, the spectroscopic factors S_n and S_p may reach maximum values of 1. The ratio of experimental values to our theoretical values is ~ 0.8, a satisfactory result in view of the notorious sensitivity of spectroscopic factors to the distorting potentials.

The bottom part of Fig. 10 shows the experimental and theoretical differences between the ^3He and t yields. The theoretical asymmetry is in general of the correct sign. Most of it comes from the Coulomb effect on the ratio $(S_n^{1/2} D_{0\,n})/(S_p^{1/2} D_{0\,p})$ and hence from symmetry breaking in the mass-3 system. The importance of symmetry-breaking Coulomb effects in the mass-3 problem has, of course, been known for some time. The isospin-multiplet relationship between ^3He and t is violated because, as a result of Coulomb distortion, the T_- operator only imperfectly connects the ^3He and t wave functions. The $\vec{T}^2$ eigenvalue is, however, still presumed to be $\frac{1}{2}$ for both states.

Our simple model can explain the major part of the observed asymmetry, but it is not yet adequate to probe the isospin-violating part of the nuclear forces by first accurately removing the Coulomb effects. There are some obvious deficiencies of the model. Firstly, it is not entirely satisfactory to put the zero range into the d-plus-nucleon vertices, since the correct angular dependence of the violation is very sensitive to the interference and should result basically from the different nucleon tails in the wave functions in the mass-3 system. Secondly, the local-energy approximation does not correctly take account of angle-dependent effects in the finite range.

But even within the framework of the DWBA, the model obviously can be improved in several respects, and the success of the present extremely simple version seems to justify the effort involved. Several possibilities for improvement are obvious. True finite-range calculations are needed for realism in discussing such light nuclei.[17] It may be necessary to antisymmetrize between the target and projectile nucleons. The use of more realistic models of the 3- and 4-particle bound states would permit a better treatment of the Coulomb perturbation and thus would enable the form factors to be calculated without resorting to the separation-energy method. Better knowledge of the distorting potentials would be of great value. Since the fore-aft asymmetry depends chiefly on the T = 1 part of χ_{t^3He}, the isospin dependence of the ^{3}He + t potential is important. Polarization

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[17] Finite-range calculations for the process ^{3}He + t → α + d performed at Florida State University are fairly successful (M. Werby, D. Robson, and S. Edwards, private communication). In those calculations (a) the finite-range DWBA was used with exchange and recoil effects included, (b) all interactions were assumed to be spin-independent and of Woods-Saxon shape, and for the potentials generating free and bound states a Coulomb potential for a uniform charge distribution was used, (c) knock-out and optical correction terms as well as pickup were included for both direct and exchange terms, (d) the interaction causing the rearrangement was taken to be charge independent, (e) nonlocalities were included in the conventional sense, and (f) spectroscopic factors for direct and exchange amplitudes were taken to be equal in magnitude.

measurements would be required in order to gain information on the isospin dependence.

As a final comment in this section, we note that the discussion of symmetry-breaking Coulomb effects in the notorious mass-3 system merely exemplifies these effects in the generality of isospin-multiplet production.

V. General Symmetry Relations and Conclusions

There is little space left to mention extensions and more applications of symmetry relations.[3] One can show that elastic scattering, multiparticle production in the final state, symmetry relations for polarizations, and substructure symmetries can all be discussed within the framework of the isospin theorem stated in Sec. I. The theorem has an extension in the case of multiplet production involving elementary particles, and there are also approximate symmetries for multiplet production.

The purpose of the discussion was to emphasize how by simple means the isospin symmetry and deviations from it give specific information about reaction mechanisms and spectroscopy. The reactions of the Barshay-Temmer type, involving the production of isospin-multiplet or isobaric-analog states, have two unique properties usually not available in (d,t), (d, ^{3}He), or other conventional reactions to analog states.[7] Firstly, the final particles are the same for both reactions and consequently the Coulomb interaction in the final channel is the same, and so is the Q value. Secondly, the fact that the amplitudes of the two reactions add coherently should enhance the sensitivity to violations of the symmetry about 90^o.

I close with a plea for a reaction theory that includes the full role of isospin. Only then can we hope to connect the problem of isospin symmetry in complex nuclei to the elementary problems of charge symmetry and charge independence.

III. ABSTRACTS OF PAPERS ACCEPTED FOR PUBLICATION

GAMMA RAYS FROM THERMAL NEUTRON CAPTURE IN ^{28}Si, ^{29}Si, AND ^{30}Si

G. B. Beard and G. E. Thomas
Nucl. Phys. (1970)

Thermal-neutron-capture γ rays from separated isotopes of silicon have been investigated. The results for the $^{28}Si(n,\gamma)^{29}Si$ reaction agreed well with those from other recent investigations in which natural silicon or enriched ^{28}Si were used as targets. The use of targets enriched in ^{29}Si and ^{30}Si markedly increased the sensitivity for detection of γ rays from excited states of ^{30}Si and ^{31}Si. A total of 28 γ rays were seen in the $^{30}Si(n,\gamma)^{29}Si$ reaction, of which 17 are included in the level diagram. For the $^{30}Si(n,\gamma)^{31}Si$ reaction, 14 transitions were observed and 13 of these are included in the accompanying level diagram. The neutron binding energies for the silicon isotopes were found to be

$$B_n(^{29}Si) = 8474.3 \pm 0.5 \text{ keV},$$
$$B_n(^{30}Si) = 10610.2 \pm 0.7 \text{ keV},$$
$$B_n(^{31}Si) = 6589.3 \pm 0.7 \text{ keV}.$$

GAMMA RAYS FROM NEUTRON CAPTURE IN RESONANCES

Lowell M. Bollinger
Experimental Neutron Resonance Spectroscopy
(Academic Press Inc., New York, 1970), Chap. IV

This article is a 110-page contribution to the book Experimental Neutron Resonance Spectroscopy, edited by J. A. Harvey and published by Academic Press, Inc. The article is a complete and critical review of the experimental information (available up to April 1968) on the characteristics and uses of γ rays resulting from the capture of neutrons in resonances.

The subjects covered in the paper are indicated by the following outline.

I. General characteristics of neutron-capture γ rays
II. Apparatus
  A. Measurements with slow-neutron spectrometers
    1. Sources of neutrons
    2. Gamma-ray spectrometers
    3. Information storage and sorting
  B. Measurements with pulsed electrostatic accelerators
  C. Measurements with filtered reactor neutrons
    1. Neutron-beam experiments
    2. Internal-target arrangement
III. Analysis of spectra
IV. Experimental results
  A. High-energy transitions
    1. Distribution of partial radiation widths
    2. Interference between resonances
    3. Correlation of partial radiation widths
    4. Average widths for E1 transitions
      a. Dependence on level spacing
      b. Dependence on γ-ray energy and nuclear size
    5. Influence of nuclear structure
      a. Anomalously strong transitions
      b. Correlation with the neutron width
      c. Interference effects
    6. M1 and E2 transitions
  B. Statistical characteristics of γ-ray cascades
    1. Total radiation widths
    2. Multiplicity
    3. Average γ-ray intensity
    4. Intensity of low-energy lines
  C. Determination of neutron-resonance parameters
    1. Isotopic assignment
    2. Spin assignment
    3. Parity assignment
  D. Study of bound states
    1. Low-energy γ rays
    2. High-energy γ rays
    3. Average-resonance-capture spectra

COULOMB EXCITATION OF LEVELS IN ^{105}Pd

H. H. Bolotin and D. A. McClure

Phys. Rev.

The low-lying excited states of ^{105}Pd were investigated by means of Coulomb excitation using 4.4—8.0 MeV α-particle projectiles. The γ-ray spectrum resulting from the de-excitation of these levels was recorded at each bombarding energy with the aid of a large-volume, high-resolution Ge(Li) detector. Thirteen transitions were observed that result from direct E2 excitation of ten excited states up to an excitation energy of 782 keV. The B(E2$\uparrow$) values from the ground state to each of these ten levels was determined. Several E2 transitions were found to be strongly enhanced over estimates of single-particle speed, a pattern suggestive of collective behavior. The measured B(E2) values, together with some inferred M1 transition speeds, are compared with predictions of a weak-coupling core-excitation model.

USE OF THE TWO-FREQUENCY TECHNIQUE OF PRIOR *ET AL.* FOR HFS INVESTIGATIONS OF ATOMS WITH INTEGRAL J

W. J. Childs

Phys. Rev.

It is shown that in using the two-frequency technique of Prior *et al.* for investigation of the hyperfine structure of atoms with integral J, any resonance observed may arise from a two-quantum transition ($\nu_\alpha + \nu_\beta = \Delta E/h$; $\nu_\alpha \neq \nu_\beta$) rather than from two successive single-quantum jumps. Although this feature requires that care be used in interpreting the observed resonance frequencies, it appears to extend the usefulness of the technique as a spectroscopic tool.

HYPERFINE AND ZEEMAN STUDIES OF LOW-LYING ATOMIC LEVELS OF ^{139}La, AND THE NUCLEAR ELECTRIC-QUADRUPOLE MOMENT

W. J. Childs and L. S. Goodman

Phys. Rev.

The atomic-beam magnetic-resonance technique has been used to determine the hyperfine-interaction constants A, B, and C, and electron g values g_J for all previously unstudied atomic levels of ^{139}La below 9000 cm^{-1}. The results are analyzed in detail in terms of a set of eigenvectors spanning the three configurations $5d6s^2$, $5d^26s$, and $5d^3$. Corrections for hyperfine and Zeeman interactions between all low-lying states are carried out in intermediate coupling. The value deduced from the observed hyperfine structure for Q, the ^{139}La nuclear ground-state electric-quadrupole moment, is influenced strongly by taking account of (a) the large, recently found configuration mixing between $5d6s^2$, $5d^2 6s$, and $5d^3$, and (b) the rather substantial Sternheimer shielding effects. The effects (a) and (b), though both about 30%, are in opposite directions and partially cancel. The value obtained is $Q = +0.22 \pm 0.03$ b. Although the order of consistency between the experimental results and theory is encouraging, a number of problems remain.

EFFECT OF THERMAL ENERGY ON IONIZATION-EFFICIENCY CURVES OF FRAGMENT IONS

W. A. Chupka

J. Chem. Phys. (15 February 1971)

The effect of thermal energy on the shape of photoionization-efficiency curves is analyzed. Several methods for determining thresholds for de-thermalized ionization-efficiency curves are presented. The assumptions and approximations used are explicitly stated for each method. The effect of thermal energy on the photoionization-efficiency curves of some alkanes is analyzed and the results are in fair agreement with the hypothesis that thermal energy is fully effective in the dissociation of the parent ions.

CONVERGENCE OF THE SASAKAWA EXPANSION FOR THE SCATTERING AMPLITUDE

F. Coester

Phys. Rev. C (February 1971)

Sasakawa has rewritten Schrödinger's integral equation in such a manner that the inhomogeneous term has the asymptotic behavior of the exact scattering wave function. This paper gives a proof that the iterative solution for the scattering amplitude converges for all local potentials for which the function $rV(r)$ is absolutely integrable. Under very general conditions the kernel of the Sasakawa equation is a Hilbert-Schmidt kernel. The integral equation is convenient for numerical solution in both the radial representation and the momentum representation.

PROTON STRIPPING STRENGTHS FOR LEVELS OF ^{11}C

J. R. Comfort, H. T. Fortune, J. V. Maher, and B. Zeidman

Phys. Rev. C

States of ^{11}C were studied with the $^{10}B(^{3}He,d)^{11}C$ reaction at a bombarding energy of 21 MeV. The data were found to favor the assignments $J^{\pi} = \frac{7}{2}^{+}$ and $\frac{5}{2}^{+}$ to the levels at 8.65 and 8.69 MeV, respectively. A distorted-wave analysis of the angular distributions for negative-parity states in ^{11}C yielded spectroscopic factors whose relative values agreed well with the predictions of Cohen and Kurath, even though the excited-state energies were found to be in better agreement with the predictions of the unified rotational model.

ENERGY LEVELS IN ^{34}Cl FROM THE $^{33}S(^{3}He,d)^{34}Cl$ REACTION: A STUDY OF THE $(d_{3/2})^2$ AND THE $d_{3/2}f_{7/2}$ INTERACTION

J. R. Erskine, D. J. Crozier, J. P. Schiffer, and W. P. Alford*

Phys. Rev. C

The energy levels of ^{34}Cl have been studied with the $^{33}S(^{3}He,d)^{34}Cl$ reaction induced by the 14-MeV ^{3}He beam of the Argonne tandem Van de Graaff accelerator. An Enge split-pole magnetic spectrograph was used to record the deuteron spectra at scattering angles of 10—65° in 5° steps. An overall energy resolution width of 17 keV was achieved. Twenty-six levels up to an excitation energy of 4.6 MeV were observed and their spectroscopic factors were extracted. The results, when combined with previously known spin information, enable us to locate the major components of $(d_{3/2})^2$ and $d_{3/2}f_{7/2}$ configurations. The two-body matrix elements obtained here are compared with other two-body data in nearby nuclei and with calculated matrix elements.

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$^{103,105}Ru$ STATES OBSERVED IN THE REACTIONS $^{102,104}Ru(d,p)$

H. T. Fortune, G. C. Morrison, J. A. Nolen, Jr., and P. Kienle

Phys. Rev. C (January 1971)

The (d,p) reaction on ^{102}Ru and ^{104}Ru has been studied at an incident deuteron energy of 14 MeV. Proton spectra were recorded

in a broad-range magnetic spectrograph. Transferred ℓ values and spectroscopic factors were obtained by comparing the measured angular distributions with distorted-wave Born-approximation predictions. The low-lying levels of ^{103}Ru are in good agreement with the results of a recent (d,t) study; information on higher levels of ^{103}Ru and on all levels in ^{105}Ru is new. There is good correspondence between strongly excited levels in the two isotopes, although there is evidence of a higher level density in ^{105}Ru. The summed spectroscopic factors give information on the extent of filling of the neutron orbitals in the targets, and these results are in reasonable agreement with results from the (d,t) reaction and for other nuclei in this region.

AN APPARATUS FOR "CHANNELING" EXPERIMENTS

D. S. Gemmell and J. N. Worthington

Nucl. Instr. Methods (1970)

A description is given of an apparatus for use in measurements on channeling and related effects seen in the passage of charged particles through single crystals. The system features good angular resolution, suitability of use for many different types of experiment, and computer control of the goniometer and detector motions as well as of the data acquisition and analysis. Some examples of data recorded with the system are presented.

INTERPRETATION OF PHOTOIONIZATION THRESHOLD BEHAVIOR

Paul M. Guyon and Joseph Berkowitz

J. Chem. Phys. (15 February 1971)

Analytical expressions are derived for treating the threshold regions of photoionization-efficiency curves. The effects of slit width, the initial thermal energy of the molecular system, and Franck-Condon factors are considered. In the dissociative ionization of small molecules such as F_2 and HCN, discrepancies can arise from failure to take these factors into account. It is also shown that for large polyatomic molecules, the use of a Watanabe-type plot to determine the adiabatic ionization potential can lead to large errors. The paper concludes with detailed applications to HF, O_2, S_2, Se_2, Te_2, S_6, and S_8, and some general observations applicable to the diatomic halogens, hydrogen halides, and alkali halides.

ISOMER SHIFTS OF THE FIRST AND SECOND EXCITED LEVELS OF THE GROUND-STATE ROTATIONAL BAND IN ^{171}Yb

W. Henning, G. M. Kalvius,* and G. K. Shenoy*

Phys. Rev. (December 1970)

The isomer shifts of the 66.7-keV $\frac{3}{2}^- \rightarrow \frac{1}{2}^-$ and the 75.9-keV $\frac{5}{2}^- \rightarrow \frac{1}{2}^-$ gamma transitions of the $\frac{1}{2}[521]$ ground-state rotational band in ^{171}Yb have been investigated, using the Mössbauer effect. From the observed shifts, the ratio of change in mean square charge radii for the two excited states was found to be

$$\Delta\langle r^2\rangle(76)/\Delta\langle r^2\rangle(67) = +0.42 \pm 0.20.$$

The decrease of $\Delta\langle r^2\rangle$ for higher rotational excitation is in disagreement with simple collective theory, and is discussed in terms of nonadiabatic effects.

From the observed magnetic hyperfine splitting, we also deduced the ratio of nuclear g factors

$$g(76)/g(0) = +0.411 \pm 0.002.$$

This value is in excellent agreement with an earlier measurement and has been used, together with other recent data on all magnetic parameters of the $\frac{1}{2}[521]$ band, in discussing the spin-polarization effects. The mixing ratio δ^2 of the M1/E2, 66.7-keV γ transition in ^{171}Yb was redetermined, correcting carefully for finite absorber effects. The new result is

$$\delta^2 = 0.36 \pm 0.04.$$

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*Solid State Science Division.

^{87}Y STATES POPULATED BY SINGLE-PROTON STRIPPING

J. V. Maher, J. R. Comfort, and G. C. Morrison

Phys. Rev. C (February 1971)

The ^{86}Sr(^{3}He,d)^{87}Y reaction was studied at a laboratory beam energy of 20 MeV to test the possible closed-subshell behavior of the 38-proton configuration. The ground-state Q value is found to be 0.346 ± 0.015 MeV. Several new states were identified below an excitation energy of 3.45 MeV. A distorted-wave analysis was used to assign ℓ values for the stripping transitions. Spectroscopic strengths agree well with sum-rule expectations for the 2p, 1f, and $1g_{7/2}$ configurations. Comparison with the results of Picard and Bassani

for the $^{88}Sr(^{3}He,d)^{89}Y$ reaction indicates qualitative agreement with shell-model expectations for 2p and 1g strengths but significant deviations for 1f strength and for low-lying 2d strength.

K_L AND K_S AS SHELL-MODEL EIGENSTATES II

K. W. McVoy and W. J. Romo

Ann. Phys. (N. Y.)

The Wigner-Weisskopf mass matrix for the neutral K-meson system has two right and two left eigenstates. The relations of these states to each other, to the eigenstates of the true Hamiltonian, and to the symmetry properties of the system are discussed in detail. The generalization to the case of three overlapping resonances is worked out as well.

ON THE REPULSION OF SLOW NEUTRONS BY ATTRACTIVE POTENTIALS

M. Peshkin and G. R. Ringo

Am. J. Phys. (1971)

A naive calculation of the scattering of slow neutrons by an attractive square-well potential gives a distribution of scattering amplitudes that agrees rather well with available measured amplitudes for thermal neutrons.

THE MÖSSBAUER EFFECT IN DILUTE ALLOYS OF IRON IN ALUMINUM

R. S. Preston and R. Gerlach

Phys. Rev. B

The Mössbauer spectrum of dilute alloys of ^{57}Fe in aluminum has been studied. In the concentration range from 0.05 to 1.2 at.% Fe, the spectrum consists partly of a single-line component due to Fe in solid solution in aluminum metal and partly of a multiple-line component associated with Fe in Fe_4Al_{13}. These two

components can be distinguished from each other by the differences in their behavior when either concentration or temperature is varied. In the course of this investigation we achieved some understanding of two peculiar observations that had led us to undertake this study. (1) Bara et al. had obtained a succession of unusual spectra for excited ^{57}Fe nuclei formed by the decay of ^{57}Co which had been diffused into aluminum metal. We can explain their results on the assumption that the ^{57}Co first went into solid solution in the aluminum, was then converted to metallic cobalt during further heat treatments, and finally became oxidized. (2) From recoil-implanted ^{57}Fe in aluminum, Sprouse et al. had obtained a Mössbauer spectrum that appeared to consist of two poorly resolved, broad lines instead of the expected single, sharp line. We believe this modification of the spectrum must be attributed to radiation damage produced by the implantation of the ^{57}Fe atoms. In the vicinity of the final position of each implanted atom, this damage is probably in the form of lattice vacancies.

DISTORTED-WAVE ANALYSIS OF CHARGE-ASYMMETRY EFFECTS IN THE REACTION $d(\alpha,t)^3He$

A. Richter* and C. M. Vincent

Phys. Rev. Letters (16 November 1970)

The fore-aft asymmetry of the angular distribution for the reaction $d(\alpha,t)^3He$ at 82 MeV is compared with the result of a simple distorted-wave Born-approximation calculation. We find that if Coulomb effects are included, the general features of the asymmetry can be reproduced.

*On leave from the Max-Planck-Institut für Kernphysik, Heidelberg, Germany.

REACTION SYMMETRIES FOR MULTIPLET PRODUCTION

D. Robson* and A. Richter†

Ann. Phys. (N. Y.)

A theorem concerning nuclear reaction symmetries for isospin-multiplet production involving complex nuclei is proved and

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†On leave from the Max-Planck-Institut für Kernphysik, Heidelberg, Germany.

generalized. The general formalism of possible symmetry violations is presented. Elastic scattering, multiparticle production in the final state, symmetry relations for polarizations, and substructure symmetries are discussed within the framework of the theorem. It is shown that the theorem has an extension in the case of multiplet production involving elementary particles. It is studied briefly in the case of SU(3) and SU(n) multiplets. Finally, some general remarks are made about approximate symmetries for multiplet production.

CRYSTALS, SUPERCOOLED LIQUIDS, AND GLASSES IN FROZEN AQUEOUS SOLUTIONS

S. L. Ruby and I. Pelah*

Mössbauer Effect Methodology, Vol. VI (January 1971)

Aqueous solutions of HCl separate into nearly pure ice and eutectic "pockets" on cooling. The eutectic composition is near $HCl \cdot 6H_2O$ and should crystallize below $T \approx 200^{\circ}K$. However, this material is easy to supercool and even to make into a glass. If $SnCl_4$ is added to the solution, all of the tin appears in the eutectic pockets. We have used electrical conductivity and differential thermal analysis as well as Mössbauer studies to clarify these phenomena. The rms displacement of the tin atoms has been measured as a function of the temperature of all these phases. To the extent to which glasses or supercooled liquids are similar to ordinary solutions, this extends the Mössbauer technique to the study of ions in solution.

*Solid State Science Division.

MAGNETIC-DIPOLE TRANSITIONS IN THE $(\pi d_{3/2})(\nu f_{7/2})$ QUARTET

R. E. Segel, G. H. Wedberg, G. B. Beard, N. G. Puttaswamy, and N. Williams

Phys. Rev. Letters (9 November 1970)

The mean lives of the second and third excited states in ^{40}K are $(0.65 \pm 0.15) \times 10^{-12}$ and $(1.6 \pm 0.3) \times 10^{-12}$ sec, respectively. The relative speeds of the three M1 transitions between the four lowest states are incompatible with these states being pure $(\pi d_{3/2})^{-1}(\nu f_{7/2})$—even if effective moments are used; neither small components of the most likely shell-model impurities nor any possible E2 admixture improves the fit. A similar situation appears to hold in ^{38}Cl.

HYPERFINE MAGNETIC FIELDS IN USb FROM MÖSSBAUER SPECTROSCOPY

G. K. Shenoy,* G. M. Kalvius,* S. L. Ruby, B. D. Dunlap,* M. Kuznietz,* and F. P. Campos†

Int. J. Magnetism (October 1970)

The hyperfine interaction in antiferromagnetic USb was investigated using the Mössbauer technique in both ^{121}Sb and ^{238}U. A saturation hyperfine magnetic field of 170 ± 5 kOe was detected at the Sb nucleus. The presence of a unique field value at all the nonmagnetic anions is consistent with the type-I antiferromagnetic structure, determined by neutron diffraction. The anion field per unit moment in USb is about four times the value found in the analogous compound UP. This ratio of the anion fields is shown to be about equal to the ratio of the atomic hyperfine fields of Sb and P. The hyperfine field at the U nucleus is 4500 ± 200 kOe. This value scales linearly with the ordered moment at the uranium when compared to UO_2 and the free U^{4+} ion.

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*Solid State Science Division.

†Materials Science Division.

MICROSCOPIC ANALYSIS AND IDENTIFICATION OF UNNATURAL-PARITY STATES IN ^{58}Ni

M. M. Stautberg

Phys. Rev. C

A microscopic analysis of the inelastic scattering of 17.7-MeV protons from ^{58}Ni has been carried out. The angular distributions of the states at 2.900 MeV (J = 1), 3.414 MeV (J = 3), and 3.773 MeV (J = 3) are best characterized by L = 2, L = 2 + 4, and L = 2 distorted-wave curves, respectively. These combinations of J and L values identify these as unnatural-parity states. The microscopic analysis used Hamada-Johnston and Gaussian realistic interactions, a mixed-configuration ground state, and pure configurations for the excited states. Exchange effects were considered in an approximate way. Comparison of the distorted-wave curves with the data indicates that the $(p_{3/2}f_{5/2})$ configuration is predominant in the 2.900-MeV state.

LIFETIME OF THE 981-keV STATE IN ^{8}Li

M. J. Throop,* D. H. Youngblood,† and G. C. Morrison

Phys. Rev. C (February 1971)

The lifetime of the 981-keV state in ^{8}Li produced in the D(^{7}Li,p)^{8}Li* reaction was measured by the two-backing variant of the Doppler-shift attenuation method. The resulting mean life was $\tau_m = 10.1 \pm 4.5$ fsec. This result is in agreement with the shell-model prediction of Cohen and Kurath, and also with that of Barker. The large error limits preclude a detailed test of either prediction.

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†Texas A & M University, College Station, Texas.

IV. PUBLICATIONS SINCE THE LAST REPORT

JOURNAL ARTICLES AND BOOK CHAPTERS

DIRECT REACTIONS ON ^{10}Be
D. L. Auton
Nucl. Phys. A157, 305-322 (23 November 1970)
Ph.D. Thesis, University of Chicago, Chicago, Illinois (29 August 1969)

GAMMA RAYS FROM THERMAL NEUTRON CAPTURE IN ^{28}Si, ^{29}Si, AND ^{30}Si
G. B. Beard and G. E. Thomas
Nucl. Phys. A157, 520-528 (1970)

DIATOMIC IONS OF NOBLE GAS FLUORIDES
J. Berkowitz and W. A. Chupka
Chem. Phys. Letters 7, 447 (1970)

ΛN TENSOR FORCES FOR SCATTERING AND FOR THE Λ-PARTICLE BINDING IN NUCLEAR MATTER
A. R. Bodmer, D. M. Rote,* and A. L. Mazza*
Phys. Rev. C2, 1623-1648 (November 1970)

GAMMA RAYS FROM NEUTRON CAPTURE IN RESONANCES
Lowell M. Bollinger
Experimental Neutron Resonance Spectroscopy, edited by J. A. Harvey (Academic Press Inc., New York, 1970), Chap. IV, pp. 235-345

AVERAGE-RESONANCE METHOD OF NEUTRON-CAPTURE γ-RAY SPECTROSCOPY: STATES OF ^{106}Pd, ^{156}Gd, ^{158}Gd, ^{166}Ho, AND ^{168}Er
L. M. Bollinger and G. E. Thomas
Phys. Rev. C2, 1951-2000 (November 1970)

LEVEL STRUCTURE OF ^{148}Sm AND ^{150}Sm FROM AVERAGE RESONANCE NEUTRON CAPTURE
D. J. Buss and R. K. Smither
Phys. Rev. C2(4), 1513-1539 (October 1970)

*University of Illinois at Chicago Circle, Chicago, Illinois.

STUDY OF ENERGY LEVELS OF ^{29}Si
D. Dehnhard* and J. L. Yntema
Phys. Rev. C2(4), 1390-1399 (October 1970)

ISOMER SHIFTS OF THE FIRST AND SECOND EXCITED LEVELS OF THE GROUND-STATE ROTATIONAL BAND IN ^{171}Yb
W. Henning, G. M. Kalvius (Solid State Science), and G. K. Shenoy (Solid State Science)
Phys. Rev. C2, 2414-2421 (December 1970)

RADIATIVE DECAY OF $d_{3/2}$-HOLE STATES
R. E. Holland and F. J. Lynch
Phys. Rev. C2(4), 1365-1370 (October 1970)

STATES IN ^{12}B OBSERVED IN THE SCATTERING OF NEUTRONS BY ^{11}B
R. O. Lane,† C. E. Nelson,† J. L. Adams,† J. E. Monahan, A. J. Elwyn, F. P. Mooring, and A. Langsdorf, Jr.
Phys. Rev. C2, 2097-2105 (December 1970)

SPIN DEPENDENCE IN INELASTIC SCATTERING
J. C. Legg,‡ D. R. Abraham,‡ J. L. Yntema, R. C. Bearse, and H. T. Fortune
Phys. Rev. C2, 1733-1737 (November 1970)

REVIEW OF "M. STANLEY LIVINGSTON, PARTICLE ACCELERATORS; A BRIEF HISTORY"§
J. J. Livingood
American Scientist 58, No. 1, 118 (1970)

NUCLEAR STRUCTURE OF Sc^{48} FROM THE $Ti^{49}(d,He^3)Sc^{48}$ REACTION
H. Ohnuma* and J. L. Yntema
Phys. Rev. C2, 1725-1728 (November 1970)

ISOSPIN NONCONSERVATION IN THE $^{28}Si(d,\alpha_1)^{26}Al_{0.23,T=1}$ REACTION
A. Richter, L. Meyer-Schützmeister, J. C. Stoltzfus, and D. von Ehrenstein
Phys. Rev. C2(4), 1361-1364 (October 1970)

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*University of Minnesota, Minneapolis, Minnesota.

†Ohio University, Athens, Ohio.

‡Kansas State University, Manhattan, Kansas.

§Harvard University Press, Cambridge, Massachusetts, 1969.

DISTORTED-WAVE ANALYSIS OF CHARGE ASYMMETRY EFFECTS IN THE REACTION $d(\alpha,t)^3He$

A. Richter and C. M. Vincent

Phys. Rev. Letters 25, 1460-1463 (16 November 1970)

THE QUEST FOR SUPERHEAVIES

J. P. Schiffer

Comments on Nuclear and Particle Physics 4(2), 90 (1970)

MAGNETIC-DIPOLE TRANSITIONS IN THE $(\pi d_{3/2})(\nu f_{7/2})$ QUARTET

R. E. Segel, G. H. Wedberg, G. B. Beard, N. G. Puttaswamy, and N. Williams

Phys. Rev. Letters 25, 1352-1355 (9 November 1970)

HYPERFINE MAGNETIC FIELDS IN USb FROM MÖSSBAUER SPECTROSCOPY

G. K. Shenoy (Solid State Science), G. M. Kalvius (Solid State Science), S. L. Ruby, B. D. Dunlap (Solid State Science), M. Kuznietz (Solid State Science), and F. P. Campos (Materials Science Division)

Int. J. Magnetism 1(1), 23-28 (October 1970)

RECOILLESS RESONANCE SPECTROSCOPY OF METEORITIC IRON OXIDES

E. L. Sprenkel-Segel

J. Geophys. Res. 75, 6618-6630 (10 November 1970)

ISOBARIC ANALOG RESONANCES FROM PROTON SCATTERING ON THE BARIUM ISOTOPES

N. Williams, G. C. Morrison, J. A. Nolen, Jr., Z. Vager, and D. von Ehrenstein

Phys. Rev. C2(4), 1539-1553 (October 1970)

$^{10}B(\alpha,{}^6Li)^8Be$ REACTION AT 46 MeV AND THE CONFIGURATION OF THE ^{10}B GROUND STATE

B. Zeidman, H. T. Fortune, and A. Richter

Phys. Rev. C2, 1612-1616 (November 1970)

REPORTS AT MEETINGS

Methods and Problems of Theoretical Physics, Proceedings of the Conference, Birmingham, 4-6 July 1967, edited by J. E. Bowcock (North-Holland Publishing Co., Amsterdam, 1970)

GROUP THEORY AND THEORETICAL PHYSICS
Harry J. Lipkin
pp. 381-399

Recent Developments in Mass Spectroscopy, Proceedings of the International Conference on Mass Spectroscopy, Kyoto, 8-12 September 1969, edited by K. Ogata and T. Hayakawa (University Park Press, Baltimore/Tokyo, 1970)

MASS-SPECTROMETRIC STUDIES OF EFFECTS CONNECTED WITH MeV ION CHANNELING IN METAL MONOCRYSTALS
M. Kaminsky
pp. 1167-1172

Program of the Conference on Photoionization Phenomena and Photoelectron Spectroscopy, University of Oxford, 14-16 September 1970 (Atomic and Molecular Physics Subcommittee of The Institute of Physics and The Physical Society, London, 1970)

PHOTOELECTRON SPECTROSCOPY OF HIGH TEMPERATURE VAPORS BY USE OF A CYLINDRICAL MIRROR ANALYZER
J. Berkowitz and R. Spohr
Paper 43

Division of Nuclear Physics, American Physical Society, Houston, 15-17 October 1970

ELASTIC AND INELASTIC SCATTERING OF ^{14}N, ^{15}N, AND ^{16}O FROM ^{28}Si
K. O. Groeneveld, A. Richter, R. H. Siemssen, and G. Stoppenhagen
Bull. Am. Phys. Soc. 15, 1676-1677 (1970)

FURTHER DEVELOPMENTS IN THE ENERGY-LEVEL STATISTIC $\Lambda(n)$
J. E. Monahan and N. Rosenzweig
Bull. Am. Phys. Soc. 15, 1668 (1970)

Division of Nuclear Physics, APS, Houston (cont'd.)

GAMMA-RAY TRANSITIONS IN $^{46,47}Ti$
H. E. Siefken,* L. Meyer-Schützmeister, J. W. Smith, G. Hardie,† and P. P. Singh‡
Bull. Am. Phys. Soc. 15, 1673 (1970)

IDENTIFICATION AND DISTORTED-WAVE ANALYSIS OF UNNATURAL-PARITY STATES IN ^{58}Ni
M. M. Stautberg
Bull. Am. Phys. Soc. 15, 1681 (1970)

Division of Plasma Physics, American Physical Society, Washington, D.C., 4-7 November 1970

RADIOFREQUENCY CONFINEMENT AND STOCHASTIC HEATING OF PLASMAS
Albert J. Hatch
Bull. Am. Phys. Soc. 15, 1407 (1970)

Division of Electron and Atomic Physics, American Physical Society, Seattle, 23-25 November 1970

HYPERFINE STRUCTURE OF $Nd^{143,145}$
W. J. Childs
Bull. Am. Phys. Soc. 15, 1521 (1970)

LANDÉ g FACTOR OF ^{254}Fm
L. S. Goodman, H. Diamond (Chemistry), H. E. Stanton, and M. S. Fred (Chemistry)
Bull. Am. Phys. Soc. 15, 1521 (1970)

Division of Nuclear Physics, American Physical Society, New Orleans, 23-25 November 1970

REACTION SYMMETRIES FOR ISOSPIN-MULTIPLET PRODUCTION
A. Richter
Bull. Am. Phys. Soc. 15, 1317 (1970)

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*Greenville College, Greenville, Illinois.

†Western Michigan University, Kalamazoo, Michigan.

‡Indiana University, Bloomington, Indiana.

STUDENT REPORTS

OPTICAL MODEL STUDIES OF HEAVY-ION SCATTERING EXPERIMENTS

William R. Fuller

CSUI-ANL student report to Trinity College, Hartford, Connecticut (Fall 1970)

MULTI-WIRE PROPORTIONAL COUNTERS FOR POSITION AND ENERGY RESOLUTION

J. C. Hayward, Jr.

CSUI-ANL student report to Wheaton College, Wheaton, Illinois (Fall 1970)

V. PERSONNEL CHANGES IN THE ANL PHYSICS DIVISION

NEW MEMBERS OF THE DIVISION

Resident Associate

Dr. Ben Greenebaum, University of Wisconsin - Parkside, Kenosha, Wisconsin. Hyperfine structure of ^{195}Pt. (Faculty Research Participation Program, ACEA affiliate.) Came to Argonne on 29 December 1970.

Graduate Student (Thesis)

Mr. Earl H. Sexton, State University of New York at Albany, New York. Working with A. J. Elwyn on polarization of neutrons from (p,n) reactions. (Resident Associate, Thesis Parts Program, ACEA affiliate.) Came to Argonne on 16 December 1970.

Graduate Student (Non-thesis)

Mr. William C. Wilkin, University of Chicago, Chicago, Illinois. Working with J. P. Schiffer on analysis of data. (Resident Student Associate.) Came to Argonne on 5 October 1970.

Scientific Assistant

Mr. Peter A. Reed joined the Physics Division on 2 December 1970 to work with G. J. Perlow.

PART-TIME APPOINTMENT

Dr. Gilbert J. Perlow became editor for the Journal of Applied Physics and Applied Physics Letters on 16 September 1970.

DEPARTURES

Mr. John D. Oyler, scientific technician, has been in the Physics Division since 11 April 1962. He terminated at ANL on 16 October 1970.

Dr. Achim Richter, postdoctoral appointee from the Max-Planck-Institut für Kernphysik, Heidelberg, Germany, has been on the staff of the ANL Physics Division since 2 December 1968. He has worked on nuclear-reaction and nuclear-structure studies at the tandem and cyclotron. He terminated at ANL on 25 November 1970 to return to the Max-Planck-Institut.